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Introduction

Fungicide resistance has developed in some diseases of row crops as well as specialty crops. This implies that fungicide applications to control such diseases may no longer be effective. Scientific studies have shown that fungicide resistance develops through natural selection of a mutant strain of a pathogen in a population that is resistant to fungicides. Resistance is very difficult to eliminate but can be delayed through appropriate management practices. The availability of inexpensive options with single mode of action products being available makes this an important issue so we do not repeat what was done in weed management.

The organization known as the Fungicide Resistance Action Committee (FRAC) was established by industry and research scientists to be an overseeing group to monitor fungicide resistance and provide guidelines for development of products with long term utility. This committee established the FRAC code which identifies different target sites within specific modes of action for all active ingredients. Usually, there is a small rectangular box on every fungicide label where the FRAC number is located (Table 1). When the FRAC code shows only one number, it implies that the fungicide contains a single active ingredient but if a fungicide contains two active ingredients, two numbers will be shown. For example, a FRAC code shown as 'group 7' indicates that the fungicide is a succinate dehydrogenase inhibitor (SDHI) whereas group 11 are Quinone outside inhibitors (QoI which includes strobilurins). However, if both 7 and 11 appear in the label, it means the fungicide has active ingredients belonging to the two groups. Some specific examples of fungicide resistance that have been seen in different crops and are discussed below. If a fungus is resistant to a specific fungicide active ingredient within a FRAC Code, then it will most likely be resistant to all fungicides with the other active ingredients in the same FRAC Code.

Frogeye Leaf Spot of Soybean

Frogeye leaf spot caused by the fungus *Cercospora sojina* is becoming a common foliar fungal disease in Nebraska. The disease is most severe when soybean is grown continuously in the same field, particularly in fields where tillage is reduced, since this is a residue-borne disease. The primary source for this disease is infested residue, infected seed and airborne spores.

In 2010, resistance to strobilurin fungicide (QoI) was reported for the first time to this pathogen in Tennessee. Since this time there has been significant spread in the Mississippi valley but we have not observed this in Nebraska yet. Current distribution of confirmed resistant populations are located on the IPM PIPE website (http://frogeye.ipmpipe.org/cgi-bin/sbr/public.cgi).
Resistance to QoI fungicides in *C. sojina* is a result of a single site mutation. This mutation is not known to have any fitness cost and has resulted in it being held in the population once it occurs.

General Management of Frogeye Leaf Spot

Resistance

Soybean varieties vary in their resistance to Frogeye Leaf Spot and there are several genes commonly used for resistance. This will reduce inoculum and exposure to fungicide for selection of resistance.

Cultural Practices

Frogeye Leaf Spot is more severe in continuously cropped soybean fields. Reduced tillage systems will tend to have more as the pathogen overwinters in residue. This will reduce inoculum levels and exposure to fungicide for selection of resistance.

Fungicide Application

Application of fungicides to manage frogeye leaf spot in Nebraska is typically not warranted in most fields. Fields with a history of frogeye should be watched carefully and if disease develops application of a strobilurin fungicide at the R3 (pod set) – early R4 growth stage are considered the most effective. Avoid applying products when disease development is significantly developed.

Gray Leaf Spot of Corn

The disease, gray leaf spot of corn, is a common fungal disease in much of Nebraska. The causal agent, *Cecospora zeae-maydis* (Czm), is closely related to the fungus causing frogeye leaf spot of soybean, being in the same genus, *Cercospora sojina*, albeit a different species. These pathogens have many biological characteristics in common, such as survival in infested plant debris from the previous season(s) and have similar weather conditions that are favorable for disease development, namely warm temperatures and high relative humidity. Whereas fungicide resistance to strobilurin fungicides (QoI fungicides) has been well-documented in the soybean frogeye leaf spot pathogen in other parts of the U.S., there have not been confirmed reports of fungicide resistance for the gray leaf spot pathogen of corn in the field. But, fungicide resistance has been documented in the laboratory in vitro tests where the fungus can utilize alternative respiration pathways to overcome the effects of the fungicides allowing for spore (conidia) germination. Baseline QoI fungicide sensitivities were identified for the gray leaf spot fungus collected from several states (including Nebraska). The results of these experiments indicated that resistance is possible in naturally-occurring populations, but that it may be less likely than in other closely related species. However, frequent applications of QoI fungicides over a large area of corn increases the probability that fungicide resistance may develop. Populations of the fungus should continue to be monitored over time to assess for a reduction in fungicide sensitivity.

Management of Gray Leaf Spot

Hybrid resistance

Corn hybrids vary widely in their resistance to gray leaf spot, which reduces the size and number of lesions. Disease immunity does not exist and highly resistant hybrids may still develop some lesions. Consult ratings provided by seed companies to help predict how the hybrid will react to gray leaf spot and position more resistant hybrids in fields with a history of severe disease and other high risk factors, such as continuous corn and minimum tillage.

Cultural practices

Residue management with tillage may provide some benefits for disease reduction, but is not practical for all production systems or locations. Tillage buries infested crop debris promoting degradation and reduces overwintering inoculum of the fungus causing disease. Crop rotation to nonhost crops can provide similar benefits, although neither strategy eliminates the risk of some disease, especially during seasons with very favorable weather conditions.

Fungicides

Foliar fungicides can be very effective at managing gray leaf spot when applied at optimal times. Applications of fungicides are most effective when applied before severe disease development and can be economical, especially in high-yielding, susceptible hybrids. Minimizing the disease in the upper plant canopy during grain fill reduces its impact on yield.

Integrated management

Deploying a combination of management strategies is more likely to provide satisfactory results. Planting more resistant hybrids in high risk production systems and monitoring disease development and progression up the plants in susceptible hybrids to make fungicide application decisions can more effectively manage gray leaf spot.

Fusarium Head Blight of Wheat

Fusarium head blight (FHB), also known as scab, is a destructive disease of wheat. In North America, it is caused primarily by *Fusarium graminearum*. The disease causes premature bleaching of spikelets, causing sterility or production of discolored, shriveled kernels commonly referred to as Fusarium-damaged or “tombstone” kernels. In addition, *F. graminearum* produces trichothecene mycotoxins, mainly deoxynivalenol (DON) and nivalenol, which contaminate grain and are harmful to humans and animals. FHB epidemics occur sporadically in Nebraska due to a variable climate. The disease tends to occur during years with high rainfall before and during flowering. The most recent major epidemics occurred in 2007, 2008, and 2015.

FHB is controlled by applying a triazole fungicide to the heads during the flowering growth stage. Triazoles used for FHB control include tebuconazole, prothioconazole, and metconazole. In 2011, the first isolate of *F. graminearum* resistant to tebuconazole was collected from a wheat spike during a survey in Steuben County, New York. It is the first tebuconazole-resistant field isolate of *F. graminearum* reported in the Americas. *F. graminearum* resistance to triazole fungicides has not been documented in Nebraska. However, the discovery of a tebuconazole-resistant isolate in New York indicates that the potential exists for resistance to develop in Nebraska isolates.

Management of FHB

Cultivar Selection

The majority of wheat cultivars grown in Nebraska have little or no resistance to FHB. Breeding efforts in recent years have yielded several cultivars in the central Great Plains States with moderate resistance to FHB. They include Overland, Everest, and Lyman. Because *F. graminearum* infects wheat heads mostly during flowering, planting cultivars with different flowering dates increases the probability that some can escape infections.

Cultural practices

Because FHB epidemics are initiated by inoculum produced on crop residues, reducing residue can reduce inoculum potential. In Nebraska, a practical cultural management practice that can reduce residue-borne inoculum is rotation with non-host crops such as soybean and alfalfa. Irrigation management to allow the crop canopy to dry between irrigations can reduce disease severity.

Fungicides

The two most effective fungicides in controlling FHB are Prosaro (prothioconazole + tebuconazole) and Caramba (metconazole). Fungicide application should be timed to protect the head. Optimal timing is at approximately 15% flowering (Feekes 10.51). Thorough coverage of heads is essential for maximum control.

Biological control

Certain bacteria and fungi have been identified that are antagonistic to *F. graminearum*, but their efficacy in the field has been poor and commercial formulations are not available. Significant progress has been made in Canada where the fungus *Clonostachys rosea* has been formulated to a product that is effective in reducing production of perithecia (sexual fruiting structures) on crop residues by *Gibberella zeae* (sexual stage of *F. graminearum*) and in suppressing FHB in the field.

Integrated Management

Because of the lack of highly resistant or tolerant cultivars, integrating available FHB management strategies is the best approach to managing the disease. Use of moderately resistant cultivars with different flowering dates, residue management, crop rotation, irrigation management, and judicial use of fungicides should all be integrated into an FHB management program.

Ascochyta Blight of Chickpea

Ascochyta blight, caused by the fungal pathogen, *Ascochyta rabiei*, is the most serious and damaging disease of chickpeas worldwide. It attacks all aerial parts of the chickpea plant, and is considered to be the primary constraint to successful chickpea production wherever the crop is grown. The pathogen can survive in both crop residue and infected seeds, which also represents the major source of spread and dissemination.

Resistance to strobilurin fungicides by *A. rabiei* was first noted from North Dakota and Montana in 2005 and 2007, respectively. In 2010, fields in South Dakota and Nebraska exhibited limited disease management after being treated with pyraclostrobin (Headline). Isolates from these locations were confirmed to contain a gene mutation which has been previously correlated with resistance to QoI fungicides in other fungal pathogens.

Management of Ascochyta Blight

Resistance

Until recently, only moderately resistant cultivars have been available, but none were completely resistant, requiring additional integrated techniques for better control. A new regionally adapted, resistant cultivar has been developed, but is currently being increased and will not be available for commercial use for another several years.

Cultural

Due to the seed- and residue-borne nature of the pathogen, burial of residue and seeds from harvest losses from infected crops and rotating out of chickpeas will help reduce pathogen populations.

Chemical

Seed treatments will help to suppress early infection and improve stand establishment, but will not provide season-long protection. Fungicide applications can also be used to reduce losses, but due to the known presence of resistant pathogen populations in Nebraska, care must be taken to select the proper chemicals for use. Although resistance in Nebraska has only been identified to pyraclostrobin, the use of azoxystrobin (Quadris) should also be discontinued. Resistance also to azoxystrobin is unproven, but still highly probable.

Optimal Ascochyta blight management in chickpeas in the future will most likely consist of an integrated approach utilizing crop rotation, genetic resistance, and fungicidal seed treatments and foliar applications with varying modes of action other than the strobilurin fungicides.

Risk Factors for Development of Fungicide Resistance

- Repeated applications during a single or across multiple growing seasons
- Use of products with active ingredients with only one FRAC code.
- Applications made after disease symptom development
- Application of reduced rates of fungicides
- Certain fungicide classes and some fungal pathogens have been identified by FRAC as being at greater risk

Management Recommendations

While fungicide resistance cannot be eliminated, it can be managed to reduce the potential for development. New fungicide groups are not easily identified and currently there are only 3 main FRAC codes used in our main crop production systems. Therefore it is critical that we take steps to prolong the usefulness of the current products.

The following recommendations should be considered when using a fungicide:

- Fungicides should be applied when disease development is at a low level of severity to avoid high numbers of the pathogens spores being exposed (selected) to the fungicide.
- Use fungicides containing more than one FRAC code.
- When using single mode of action fungicides - Tank-mix more than one fungicide with a different FRAC code.
- Use labelled rates and avoid using reduced rates. Know the risk factors associated with reduced rates for specific FRAC codes (i.e. - reduced rates of triazole fungicides increase the risk of resistance).
- Evaluate the level of disease control after an application is made. If you suspect you are having reduced control resistance may be occurring. Contact your local University of Nebraska Extension employee if you believe fungicide resistance may be an issue in your field. It will be important to report this quickly so that the selection pressure is not continued in the region.

Additional Resources

Additional information on identification of common field crop diseases can be found at: http://cropwatch.unl.edu/plantdisease

Giesler, L., Bradley, C., Chilvers, M., Freije, A., Mueller, D., Sisson, A., Smith, D., Tenuta, A., and Wise, K. 2016. Frequently asked questions about fungicide resistance in field crop diseases. Website: Crop Protection Network. CPN 4001. http://cropprotectionnetwork.org/general-crop-management/faqs-about-fungicide-resistance/

Bradley, C. A., Hollier, C., and Kelly, H. Principles of Fungicide Resistance. Plant Management Network. https://www.plantmanagementnetwork.org/hub/soyfungicideresistance/files/FungicideResistance.pdf

Bradley, C. A., and Pedersen, D. K. 2011. Baseline sensitivity of *Cercospora zeae-maydis* to quinone outside inhibitor fungicides. Plant Disease 95:189-194.

Table 1. Example of Fungicide Resistance Action Committee (FRAC) fungicide classification for azoxystrobin and propiconazole.

Fungicide active ingredient	FRAC Code	Group Name	Chemical group	Mode of Action
azoxystrobin	11	Quinone outside inhibitor (QoI)	Methoxy-acrylates (strobilurin)*	Respiration inhibitor
propiconazole	3	Demethylation inhibitor (DMI)	Triazole	Sterol biosynthesis in membranes

*Fungicides in this group are commonly referred to as strobilurins, however these active ingredients are no longer specified as strobilurins by FRAC. (Originally developed in Giesler et al., 2016)).